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WAVELENGTH SCALING FOR REACTOR-SIZE LASER FUSION TARGETS. (U)  
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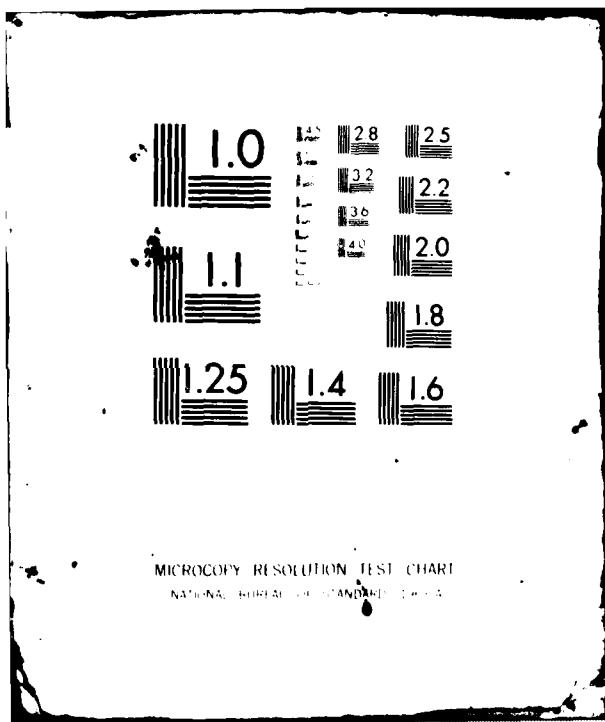
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## WAVELLENGTH SCALING FOR REACTOR-SIZE LASER FUSION TARGETS

In order to achieve high pellet gains for laser fusion, one must control a number of distinct critical physics elements.<sup>1</sup> Two of these elements are a sufficient coupling efficiency of laser energy into the imploding DT fuel (5-10%), and a low fuel preheat (2-4 times Fermi temperature). To satisfy these conditions one must limit the deleterious plasma instabilities, such as stimulated backscatter and suprathermal electron generation. It has been widely suggested that this control be accomplished first by use of thin-shell<sup>2</sup> or double-shell<sup>3</sup> pellet designs that use a lower peak laser irradiance, and second by the use of shorter laser wavelengths<sup>4</sup> in the range  $\frac{1}{2}$  to  $\frac{1}{4}$  micron since the strength of many of the plasma instabilities scales as  $I \lambda^2$ .

This article will present the scaling law of another critical element: the symmetry of the pellet implosion. For high gain, the asymmetry of the ablation pressure must be less than a few percent;<sup>1</sup> i.e.  $\delta P/P \leq 1-3\%$ . Either the laser illumination on the pellet must also be uniform to this percentage, or one needs some physics mechanism to smooth out the laser nonuniformities. Nuckolls et al.<sup>5</sup> proposed such a physics mechanism: by designing their shaped-pulse pellet so that the distance D between the laser absorption surface and the ablation surface was itself on the order of the pellet radius, ( $D \sim R$ ), lateral thermal conduction could smooth out the laser nonuniformities, yielding  $\delta P/P \ll \delta I/I$ . Such smoothing has been observed experimentally.<sup>6</sup> Using a hydrodynamic computer code, we have found a scaling law for this separation distance D. This D scales much more strongly with wavelength than do the plasma instability effects. We find  $D \sim (I \lambda^{3.8})^{0.7}$  for a given pellet size. This places a strong premium on the use of longer laser wavelengths, in the near-infrared, for reactor-sized

(1-5 mm) pellets. Plasma instabilities may then have to be controlled by other techniques, such as the use of a very broad-band laser, and/or the use of thinner pellet shells. (Symmetrization by the use of x-ray coupling is not considered in this article.)

Because the code compares well with experimental data at the Naval Research Laboratory on ablation pressures, mass ablation rates, and target velocities from the ablative acceleration of flat targets,<sup>7</sup> we have a degree of confidence in our scaling result. Our code also has some distinctive capabilities, discussed below. We have also applied the code to a study of the higher density region of the pellet when driven by moderate laser intensities, ( $\leq 10^{14}$  W/cm<sup>2</sup>) where fewer uncertain plasma effects exist.

The Model. We used 1-D spherical hydrodynamics, with time-dependent equations for continuity of mass, momentum, and energy, including light pressure. The laser light not absorbed by inverse bremsstrahlung was deposited smoothly over two zones including the critical surface, so as not to generate artificial shocks.

Thermal conduction was computed using the usual smoothing technique with the conduction coefficient given by  $1/K = 1/K_{cl} + 1/K_{fl}$ , with  $K_{cl}$  from Spitzer-Harm, and  $K_{fl} = f \sqrt{kT/m_e} n_e kT/|vT|$ . The flux-limiter  $K_{fl}$  is a construct used in fluid codes, for which there are not tests yet on reactor-sized plasmas. We tried values for  $f$  ranging from 0.6 to 0.03. We have presented results using the Bell-Evans-Nicholas value of  $f=0.1$  which we believe to be on the surest theoretical grounds. The separation distance  $D$  is rather insensitive to  $f$ , for  $f > 0.1$ , as long as the Mach number at the critical surface is also not too much greater than one (in other words,

small spherical divergence).<sup>9</sup> For  $f = 0.03$  the flow Mach number is limited to less than 0.5 in the overdense region, and then the separation distance  $D$  is reduced by a factor of 3 to 4.

The equations were integrated in strict conservation form, guaranteeing correct motion of shock waves in the accelerated dense shell. Pressure and temperature were thus derived by subtracting directed kinetic energy from total energy. The fluid equations were closed with equations of state that express  $P = F(E, \rho)$  and  $T = G(E, \rho)$ . Near the ablation surface these equations of state must include the effects of solid material, Fermi-temperature, and fractional ionization. We based our equation of state on the solid material models used in the analytic model (ANEOS) in the CHARTD code,<sup>10</sup> and expansions of the Fermi-Dirac functions by Clayton,<sup>11</sup> incorporating a phenomenological cold compression curve to model the bulk modulus and the binding energy of the atoms. This model goes smoothly from a Thomas-Fermi-Dirac model for degenerate electrons at high density and low temperatures to a Saha equilibrium at high temperatures and low densities. Such a treatment is necessary in order to correctly calculate the acceleration of near-solid, low-temperature target shells without having the shell compress or explode unrealistically.

The equations were integrated numerically with a sliding zone, Eulerian, flux-corrected-transport (FCT) code and solved with a flux-conserving scheme such that the fluxes between zones result from the difference in fluid and grid velocities. The outer boundary zones moved in a Lagrangian manner, while the intermediary zones moved in a prescribed smooth continuous manner. Near the ablation surface, the mass per unit zone was chosen proportional to the density (constant zone size). Beyond the ablation

surface, the mass per zone continually decreased until it reached a minimum value. Thereafter the mass per zone was held fixed up to the critical surface (increasing zone size). Outside the critical surface, the mass per zone increased exponentially. This technique allows a grid resolution of a few tenths of a micron near the ablation surface; it also has the distinct advantage over purely Lagrangian codes of not wasting zones where not needed.

Rather than attempt to design a set of optimized implosions, we chose pure CH shells of constant thickness of  $125 \mu\text{m}$ . We used no prepulses to generate an artificially large initial separation distance D, since so far such prepulses have led to shock heating that is unacceptable for high gain pellets. The results here are expressed in terms of absorbed irradiance, since the absorption process is not well understood for reactor-sized pellets. (Based on current knowledge, we guess that net absorptions will lie in the range of 40% - 90% for the intensity-wavelength regimes treated in this article.) Reactor-sized pellets will have radii of 1-5 mm. Since laser energy scales as  $R^3 (\Delta R/R)$ , a much larger radius would imply an excessive aspect ratio or excessive laser energy. A smaller radius cannot contain sufficient fuel for efficient burn and high gain. The intensity profile was ramped linearly for 2 nsec, followed by  $I_a(t)R^2(t) = \text{constant}$ . The last variation had no appreciable effect, since we found our quasi-steady profiles by looking early in time before the bulk of the shell had moved inward appreciably.

The Results. Calculations at laser wavelengths of  $0.53 \mu\text{m}$ ,  $1.06 \mu\text{m}$ , and  $2.7 \mu\text{m}$  with pellet radii of 1mm, 2mm, and 5mm were used to derive scaling laws for the pressure P and the separation ratio D/R versus laser

intensity, laser wavelength, and pellet radius. A least squares fit of the form  $P \sim (I_a \lambda^{-0.25} R^{-0.18})^{0.7}$  is shown in Figure 1. Figure 2 shows D/R versus laser intensity for three wavelengths and two initial radii. We found a least squares fit of the form

$$\frac{D}{R} \sim \frac{(I_a \lambda^{3.8})^{0.7}}{R + B}$$

In the region of interest,  $B \approx 1\text{mm}$ , and is only weakly dependent on  $I_a$  and  $\lambda$ .

This form goes to the correct limits for both large and small radii.

This surprisingly strong wavelength dependence is the result of two factors: longer wavelength light is absorbed at lower densities, and these lower densities have longer scale lengths.

Emery et al.<sup>12</sup> have shown, for flat geometry, that if the separation distance D is more than 0.3 times the laser inhomogeneity wavelength, then  $\delta P/P \leq 0.1 \delta I/I$ . We expect roughly the same factor of ten smoothing in spherical geometry, if  $D/R = 0.3$ . From Figure 2, this implies a minimum laser intensity of about  $0.5 - 2 \times 10^{13} \text{ W/cm}^2$  with  $2.7 \mu\text{m}$  light, about  $0.8 - 2 \times 10^{14} \text{ W/cm}^2$  with  $1\mu\text{m}$  light, and more than  $10^{15} \text{ W/cm}^2$  with  $0.5 \mu\text{m}$  light. Still shorter laser wavelengths, of  $1/3$  to  $1/4$  micron, would require much higher laser intensities.

For today's moderate aspect ratio pellet, with  $R_o/\Delta R_o = 8-20$ , an ablation pressure of about 10-30 megabars is required to drive the shell inward to fusion-level velocities, using a relatively unshaped laser pulse. Extrapolating from Figure 1, we see that the optimal laser intensity is probably a few times  $10^{14} \text{ W/cm}^2$ . It appears that a one micron laser should suffice for producing both sufficient ablation pressure and sufficient 2-D

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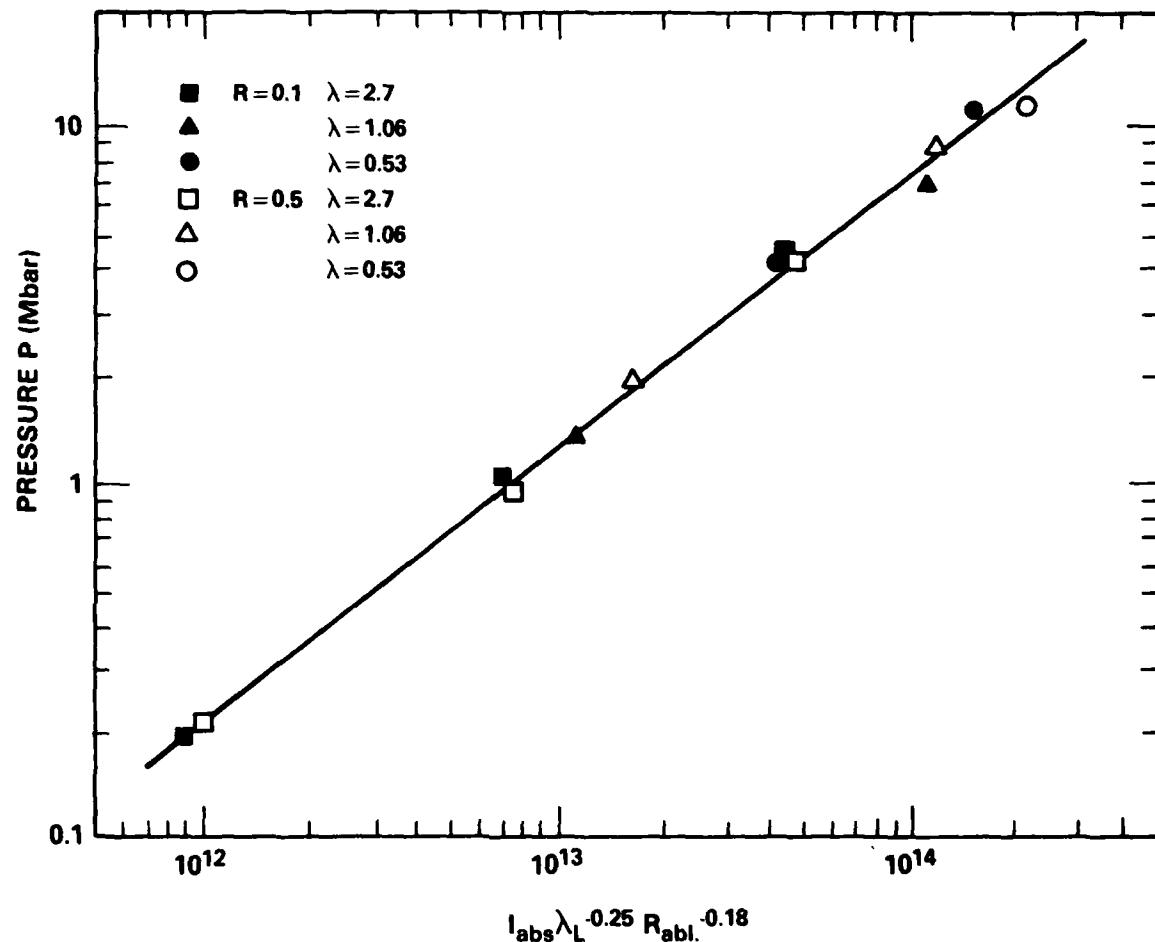


Fig. 1 — Ablation surface pressure scaling, with several laser wavelengths and radii

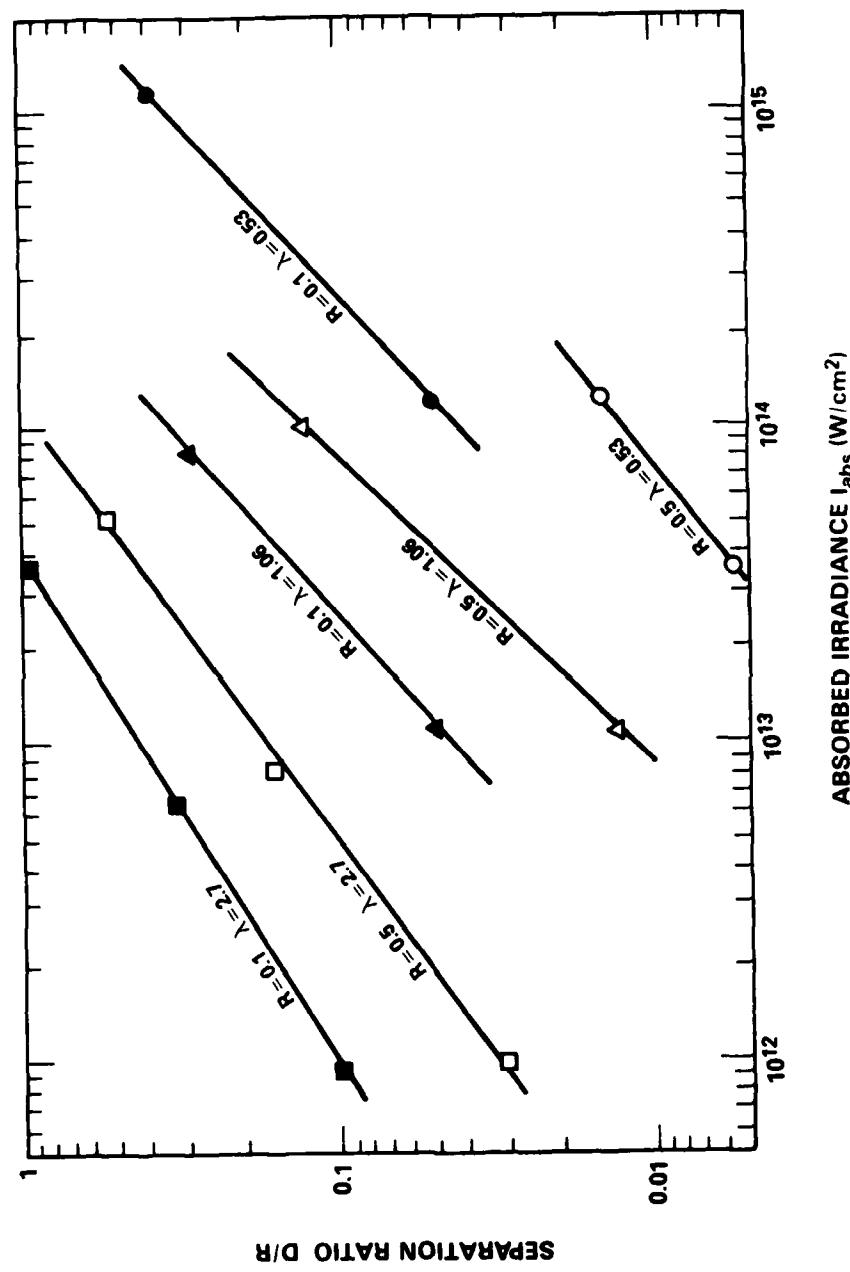


Fig. 2 — Ratio of the distance from the critical surface to the ablation surface, for several laser wavelengths and radii. Separation distance is strongly dependent on laser wavelength. A flux limit value of  $f = 0.03$  would reduce  $D/R$  by roughly a factor of 3-4.

smoothing. (For a flux limit of  $f = 0.03$  the optimal wavelength would increase to two to three microns.)

### Discussion

Why not use a shorter laser wavelength? To keep the same smoothing factor in the same size pellet with a  $\frac{1}{2}$  micron laser, we would need an intensity that was increased by about the factor  $2^{3.8} = 14$ . Then the plasma instability parameter  $I\lambda^2$  would increase by the factor 3.5. Therefore shorter wavelengths, for the same amount of smoothing, would actually increase the potential for plasma instabilities. Equally important, the ablation pressure at the higher laser intensity might be too large, thereby driving strong shocks through the shell that would preheat the pellet fuel. If one reverts to a shaped-pulse pellet concept, one can use these higher laser intensities, but only after the pellet shell has moved significantly inward, again with unacceptable asymmetries.

What about a much longer wavelength laser? There would be much more of a safety margin for lateral smoothing with a 2-3 micron laser, at the required intensity of a few times  $10^{14} \text{ W/cm}^2$ , and in fact this may be necessary. But for fixed ablation pressure, the instability factor  $I\lambda^2$  would again increase.

There seems to be a barrier at shorter wavelengths because the smoothing requirement quickly drives one to unacceptably high laser intensities and ablation pressures. And at longer wavelengths, the ablation pressure requirement on the laser intensity soon exceeds the threshold for plasma instabilities. The actual location of the wavelength window is somewhat uncertain, but it appears to lie between  $\frac{1}{2}$  micron and 2.7 microns.

Since we first proposed this wavelength window concept, there have been several suggestions for widening the window. We have suggested using a very broad bandwidth laser,<sup>1</sup> such as HF at 2.7-3.1 micron,, to raise the plasma instability threshold by an order of magnitude. Fabre<sup>13</sup> has suggested using a much smaller pellet radius R, but it would be difficult to contain enough DT fuel as stated above. Nuckolls has suggested using a variant of his old proposal<sup>14</sup> for a series of temporal changes in the laser frequency, starting at longer wavelengths for maximum smoothing, and ending with shorter wavelengths for maximum coupling efficiency.

It is best to finish with some caveats. First our hydrodynamic model, and any hydrodynamic model, tends to fail when trying to accurately treat plasma phenomena such as fast electron transport and filamentation. And the most interesting regime for reactor-sized targets is just at that irradiance where hydrodynamic models tend to fail. Second, if the long-wavelength laser-plasma coupling is poor, then there may be no intensity-wavelength window that produces sufficient symmetrization. Although there is experimental data with microwaves<sup>15</sup> that shows that a broad bandwidth raises some of the plasma instability thresholds, there is negligible data so far with broad bandwidth lasers, such as HF.

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